COSMOLOGY WITH PRIMORDIAL BLACK HOLES

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Some aspects of Cosmology with primordial black holes are briefly reviewed

1 Density upper limits

Small black holes could have formed in the early Universe if the density contrast was high enough (typically $\delta > 0.3 - 0.7$, depending on models). Since it was discovered by Hawking [1] that they should evaporate with a black-body like spectrum of temperature $T = \hbar c^3/(8\pi kGM)$, the emitted cosmic rays have been considered as the natural way, if any, to detect them. Those with initial masses smaller than $M_* \approx 5 \times 10^{14}$ g should have finished their evaporation by now whereas those with masses greater than a few times M_* do emit nothing but extremely low energy massless fields.

As was shown by MacGibbon and Webber [2], when the black hole temperature is greater than the quantum chromodynamics confinement scale Λ_{QCD}, quark and gluon jets are emitted instead of composite hadrons. This should be taken into account when computing the cosmic-ray fluxes expected from their evaporation. Among all the emitted particles, two species are especially interesting : gamma-rays around 100 MeV because the Universe is very transparent to those wavelengths and because the flux from PBHs becomes softer ($\propto E^{-3}$ instead of $\propto E^{-1}$) above this energy, and antiprotons around 0.1-1 GeV because the natural background due to spallation of protons and helium nuclei on the interstellar medium is very small and fairly well known.

Computing the contributions both from the direct electromagnetic emission and from the major component resulting from the decay of neutral pions, the gamma-ray spectrum from a given distribution of PBHs can be compared with measurements from the EGRET detector onboard the CGRO satellite. This translates (in units of critical density) into [3] : $\Omega_{PBH}(M_*) < 10^{-8}$, improving substantially previous estimates [5]. The expected gamma-ray background has also recently been taken into account to decrease this upper limit by a factor of three. Computing the contribution from unresolved blazars and the emission from normal galaxies, Pavlidou & Fields [6] have estimated the minimum amount of extragalactic gamma-rays which should be expected. The first one was computed using the Stecker-Salamon model and the second one is assumed to be proportional to the massive star formation rate (which is itself proportional to the supernovae explosion rate) as it is due to cosmic-ray interactions with diffuse gas. With a very conservative errors treatment this leads to [7]: $\Omega_{PBH}(M_*) < 3.3 \times 10^{-9}$.

On the other hand, galactic antiprotons allowed new complementary upper limits as no excess from the expected background is seen in data [8]. The main improvement of the last years is, first, the release of a set of high-quality measurements from the BESS, CAPRICE and AMS experiments. The other important point is a dramatic improvement in the galactic cosmic-rays propagation model [9]. A most promising approach is based on a two-zone description with six free parameters : K_0, δ (describing the diffusion coefficient $K(E) = K_0 \beta R^\delta$), the diffusive halo half height L, the convective velocity V_c and the Alfvén velocity V_a [10]. The latters have been varied within a given range determined by an exhaustive and systematic study of cosmic ray nuclei data [11], giving a very high confidence in the resulting limit : $\Omega_{PBH} < 4 \times 10^{-9}$ for an average halo size

[12]. This approach paid a great attention to many possible sources of uncertainties, some being shown to be very small (*e.g.* the flatness of the dark matter halo and its core radius, the spectral index of the diffusion coefficient, the number of sources located outside the magnetic halo), other being potentially dramatic (*e.g.* a possible "photosphere" around PBHs [13] which could lead to substantial interactions between partons, a cutoff in the mass spectrum if the inflation reheating temperature was to low). Furthermore, this study can be improved by taking advantage of the different ways in which solar modulation changes the primary and secondary fluxes [14].

Improvements in the forthcoming years can be expected in several directions. Gamma-rays could lead to better upper limits with new data from the GLAST satellite [15] to be launched in 2007. The background due to known gamma-ray sources could also be taken into account in the analysis. On the other hand, antiprotons should be much better measured by the AMS experiment [16], to be operated on the International Space Station as of 2006. Finally, antideuterons could open a new window for detection. The probability that an antiproton and an antineutron emitted by a given PBH merge into and antideuteron within a jet can be estimated through the popular nuclear physics coalescence model. The main interest of this approach is that the spallation background is extremely low below a few GeV for kinematical reasons (the threshold is much higher in this reaction (17 m_p) than for antiprotons), making the signal-to-noise ratio potentially very high [17] with a possible improvement in sensitivity by one order of magnitude.

An interesting alternative could be to look for the expected extragalactic neutrino background from PBHs evaporation [18]. This is an original and promising idea but it suffers from a great sensitivity to the assumed mass spectrum.

A very different approach would be to look the gravitational waves emitted by coalescing PBH binaries [19]. This could be the only possible way to detect very heavy PBHs (above a fraction of a solar mass for the current LIGO/VIRGO experiments) which do not emit any particle by the Hawking mechanism. If most of the halo dark matter was made of, say $0.5M_\odot$ PBHs (as suggested in some articles by the MACHO collaborations that are nowadays disfavoured by the EROS results), there should be about 5×10^8 binaries out to 50 kpc away from the Sun, leading to a measurable amount of coalescence by the next generation of interferometers.

2 PBH formation in cosmological models

Small Black holes are a unique tool to probe the very small cosmological scales, far beyond the microwave background (CMB) or large scale structure (LSS) measurements (see [20] for a review). In the standard mechanism, they should form with masses close to the horizon mass at a given time:

$$M_{PBH}(t)=\gamma^{3/2}M_{Hi}\left(\frac{t}{t_i}\right)=\gamma^{3\gamma/(1+3\gamma)}M^{(1+\gamma)/(1+3\gamma)}M_{Hi}^{2\gamma/(1+3\gamma)}$$

where M_H is the horizon mass, γ is the squared sound velocity, the subscript 'i' represents the quantity at t_i, the time when the density fluctuation develops, and $M\propto M_H^{3/2}$ is the mass contained in the overdense region with comoving wavenumber k at t_i. In principle, it means that PBHs can be formed with an extremely wide mass range, from the Planck mass ($\approx 10^{-5}$ g) up to millions of solar masses. Assuming that the fluctuations have a Gaussian distribution and are spherically symmetric, the fraction of regions of mass M which goes into black holes can (in most cases) be written as :

$$\beta(M)\approx\delta(M)exp\left(\frac{-\gamma^2}{2\delta(M)^2}\right)$$

where $\delta(M)$ is the RMS amplitude of the horizon scale fluctuation. The fluctuations required to make the PBHs may either be primordial or they may arise spontaneously at some epoch but the most natural source is clearly inflation [21]. Using the direct (non)detection of cosmic-rays from PBHs, the entropy per baryon, the possible destruction of Helium nuclei and some subtle nuclear process, several limits on $\beta(M)$ have been recently re-estimated [3 22]. The most stringent one comes from gamma-rays for $M \approx 5 \times 10^{14}$ g : $\beta < 10^{-28}$.

Such limits can be converted into relevant constraints on the parameters of the primordial Universe. In particular, a "too" blue power spectrum ($P(k) \propto k^n$ with $n > 1$) would lead to an overproduction of PBHs. Taking advantage of the normalization given by COBE measurements of the fluctuations at large scales, a blue power spectrum can be assumed (as favoured in some hybrid inflationary scenarii for example) and compared with the gamma-ray background as observed with the EGRET detector [23]. The resulting upper limit is $n < 1.25$, clearly better than COBE, not as good as recent CMB measurements [24 25] but extremely important anyway because directly linked with very small scales. Some interesting developments were also achieved by pointing out a systematic overestimation of the mass variance due to an incorrect transfer function [26 27], leading to a slightly less constraining value : $n < 1.32$. This approach also allowed to relax the usual scale-free hypothesis and to consider a step in the power spectrum, as expected in Broken Scale Invariance (BSI) models : too much power on small scales (a ratio greater than $\approx 8 \times 10^4$) would violate observations. The highly probable existence of a cosmological constant ($\Omega_\Lambda \approx 0.7$) should also be considered to estimate correctly the mass variance at formation time which should be decreased by about 15% [28]. More importantly, this approach showed that in the usual inflation picture, no cosmologically relevant PBH dark matter can be expected unless a well localized bump is assumed in the mass variance (either as an *ad hoc* hypothesis, either as a result of a jump in the power spectrum, or as a result of a jump in the first derivative of the inflaton potential) [29]. Nevertheless, if the reheating temperature limit due to entropy overproduction by gravitinos decay is considered [30], a large window remains opened for dark matter [31]. The main drawback of PBHs as a CDM candidate is the high level of fine tuning required to account for the very important dependence of the β fraction as a function of the mass variance.

An important constraint can also be obtained thanks to a possible increase of the PBH production rate during the preheating phase if the curvature perturbations on small scales are sufficiently large. In the two-field preheating model with quadratic potential, many values of the inflaton mass and coupling are clearly excluded by this approach [32] : the minimum preheating duration for which PBHs are overproduced, $m\Delta t$, is of order 60 for an inflaton mass around 10^{-6} and a coupling $g \approx 10^{-4}$.

Interestingly, the idea [33] that a new type of PBHs, with masses scaling as $M_{PBH} = kM_H(\delta_H - \delta_H^c)^{\gamma_s}$, could exist as a result of near-critical collapse, was revived in the framework of double inflationary models. Taking into account the formation during an extended time period, an extremely wide range of mass spectra can be obtained [34]. Such near-critical phenomena can be used to derive very important cosmological constraints on models with a characteristic scale, through gamma-rays [35] or through galactic cosmic-rays [36]. The resulting $\beta_{max}(M)$ is slightly lower and wider around $M_* \approx 5 \times 10^{14}$ g than estimated through "standard" PBHs.

Alternatively, it was also pointed out that some new inflation models containing one inflaton scalar field, in which new inflation follows chaotic inflation, could produce a substantial amount of PBHs through the large density fluctuations generated in the beginning of the second phase [37]. Another important means would be to take into account the cosmic QCD transition : the PBH formation is facilitated due to a significant decrease in pressure forces [38]. For generic initial density perturbation spectra, this implies that essentially all PBHs may form with masses close to the QCD-horizon scale, $M_H^{QCD} \approx 1 M_\odot$.

Finally, PBHs could help to solve a puzzling astrophysical problem : the origin of supermassive black holes, as observed, *e.g.*, in the center of active galactic nuclei [39]. In such models, very small black holes attain super massive sizes through the accretion of a cosmological quintessential scalar field which is wholly consistent with current observational constraints. Such a model can generate the correct comoving number density and mass distribution and, if proven to be true, could also constraint the required tilt in the power spectrum.

Another interesting way to produce massive primordial black holes would be the collapse of sufficiently large closed domain wall produced during a second order phase transition in the vacuum state of a scalar field [40].

3 PBH cosmology and fundamental physics

If the evaporation process was detected, it would mean that the Hubble mass at the reheating time was small enough not to induce a cutoff in the PBH mass spectrum which would make light black holes exponentially diluted. As some hope for future detection is still allowed thanks to antideuterons, it could be possible to give a lower limit on the reheating temperature [41]. When compared with the upper limit coming from Big-Bang nucleosynthesis [42], this translates into a lower limit on the gravitino mass. It is important to point out that such possible constraints on the gravitino mass can be converted into constraints on more fundamental parameters, making them very valuable in the search for the allowed parameter space in *grand unified* models. As an example, in models leading naturally to mass scales in the 10^2-10^3 GeV range through a specific dilaton vacuum configuration in supergravity, the gravitino mass can be related with the GUT parameters [43]:

$$m_{3/2} = \left(\frac{5\pi^{\frac{1}{2}}\lambda}{2^{\frac{3}{2}}} \right)^{\sqrt{3}} (\alpha_{GUT}) \left(\frac{M_{GUT}}{M_{Pl}} \right)^{3\sqrt{3}} M_{Pl}.$$

With $M_{GUT} \sim 10^{16}$ GeV and a gauge coupling $\alpha_{GUT} \sim 1/26$, antideuterons could probe an interesting mass range [41].

Another important challenge of modern physics is to build links between the theoretical superstring/M-theory paradigm on the one side and the four-dimensional standard particle and cosmological model on the other side. PBHs can play an important role in this game. One of the promising way to achieve a semiclassical gravitational theory is to study the action expansion in scalar curvature. At the second order level, according to the pertubartional approach of string theory, the most natural natural choice is the 4D curvature invariant Gauss-Bonnet approach:

$$S = \int d^4x \sqrt{-g} \left[-R + 2\partial_\mu \phi \partial^\mu \phi + \lambda e^{-2\phi} S_{GB} + \dots \right],$$

where λ is the string coupling constant, R is the Ricci scalar, ϕ is the dilatonic field and $S_{GB} = R_{ijkl}R^{ijkl} - 4R_{ij}R^{ij} + R^2$. This generalisation of Einstein Lagrangian leads to the very important result that there is a minimal mass M_{min} for such black holes [44]. Solving the equations at first perturbation order with the curvature gauge metric, it leads to a minimal radius :

$$r_h^{inf} = \sqrt{\lambda}\,\sqrt{4\sqrt{6}}\phi_h(\phi_\infty), \tag{1}$$

where $\phi_h(\phi_\infty)$ is the dilatonic value at r_h. The crucial point is that this result remains true when higher order corrections or time perturbations are taken into account. The resulting value should be around $2M_{Pl}$. It is even increased to $10M_{Pl}$ if moduli fields are considered, making the conclusion very robust and conservative. In this approach, the Hawking evaporation law must be drastically modified and an asymptotically "quiet" state is reached instead of the classical quadratic divergence [45]. Although not directly observable because dominated by the astrophysical background, the integrated spectrum features very specific characteristics.

A very exciting possibility would be to consider particle colliders as (P)BH factories. If the fundamental Planck scale is of order a TeV, as the case in some extradimension scenarii, the LHC would produce one black hole per second [46 47]. In a brane-world in which the Standard Model matter and gauge degrees of freedom reside on a 3-brane within a flat compact volume V_{D-4}, the relation between the four-dimensional and the D-dimensional Newton's constants is simply $G_N = G_D/V_{D-4}$ and $M_{Pl}^{D-2} = (2\pi)^{D-4}/(4\pi G_D)$. In the - not so obvious for colliders - low angular momentum limit, the hole radius, Hawking temperature and entropy can be written as :

$$R_H = \left(\frac{4(2\pi)^{D-4} M}{(D-2)\Omega_{D-2} M_{Pl}^{D-2}} \right)^{1/(D-3)} , \; T_H = \frac{D-4}{4\pi R_H} , \; S = \frac{R_H^{D-2}\Omega_{D-2}}{4G_D}$$

where

$$\Omega_{D-2} = \frac{2\pi^{(D-2)/2}}{\Gamma(\frac{D-1}{2})}$$

is the area of a unit $D-2$ sphere. Together with the black hole production cross section computation (as a sum over all possible parton pairings with $\sqrt{s} > M_{Pl}$), those results lead to very interesting observable predictions which - in spite of the "sad news" that microphysics would be screened - should allow to determine the number of large new dimensions, the scale of quantum gravity and the higher dimensional Hawking law. A direct consequence of those ideas is to look also for black hole production through cosmic-rays interactions in the Earth atmosphere. Limiting ourselves with neutrinos - to avoid diffractive phenomena - it seems that the AUGER, EUSO and OWL experiments should be sensitive to such effects [48 49].

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